Modeling the Stress Strain Behavior of Woven Ceramic Matrix Composites

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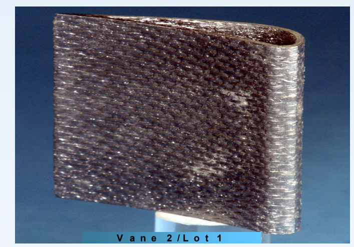
Abstract

Woven SiC fiber reinforced SiC matrix composites represent one of the most mature composite systems to date. Future components fabricated out of these woven ceramic matrix composites are expected to vary in shape, curvature, architecture, and thickness. The design of future components using woven ceramic matrix composites necessitates a modeling approach that can account for these variations which are physically controlled by local constituent contents and architecture. Research over the years supported primarily by NASA Glenn Research Center has led to the development of simple mechanistic-based models that can describe the entire stress-strain curve for composite systems fabricated with chemical vapor infiltrated matrices and melt-infiltrated matrices for a wide range of constituent content and architecture. Several examples will be presented that demonstrate the approach to modeling which incorporates a thorough understanding of the stress-dependent matrix cracking properties of the composite system.

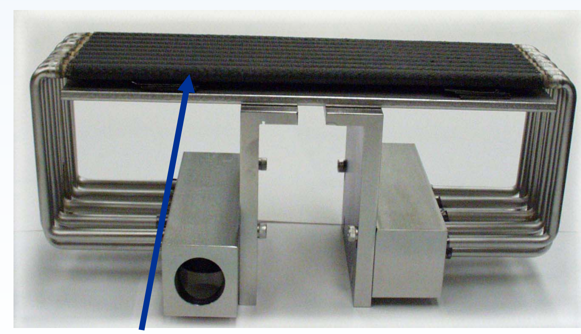
SiC/SiC Ceramic Matrix Composite Development at NASA Glenn (Lewis)

- 1990's = Enabling Propulsion Materials (EPM) Program with GE and P&W: High Speed Civil Transport Combustor Liner (1200°C, > 10,000 hours)
  - Highest temperature fiber
  - BN interphase
  - Melt (Si) infiltrated SiC matrix
- 2000's = Ultra Efficient Engine Technology (UEET) Program: 1315°C application temperature, e.g., turbine vane
  - Further improvements to fiber, interphase, and matrix
- Future? = Space Propulsion: 1450°C+ application temperatures, e.g., thin cooled structures, turbine blades…
  - Non-Si containing matrices: CVI SiC, PIP SiC

Combustor Liner

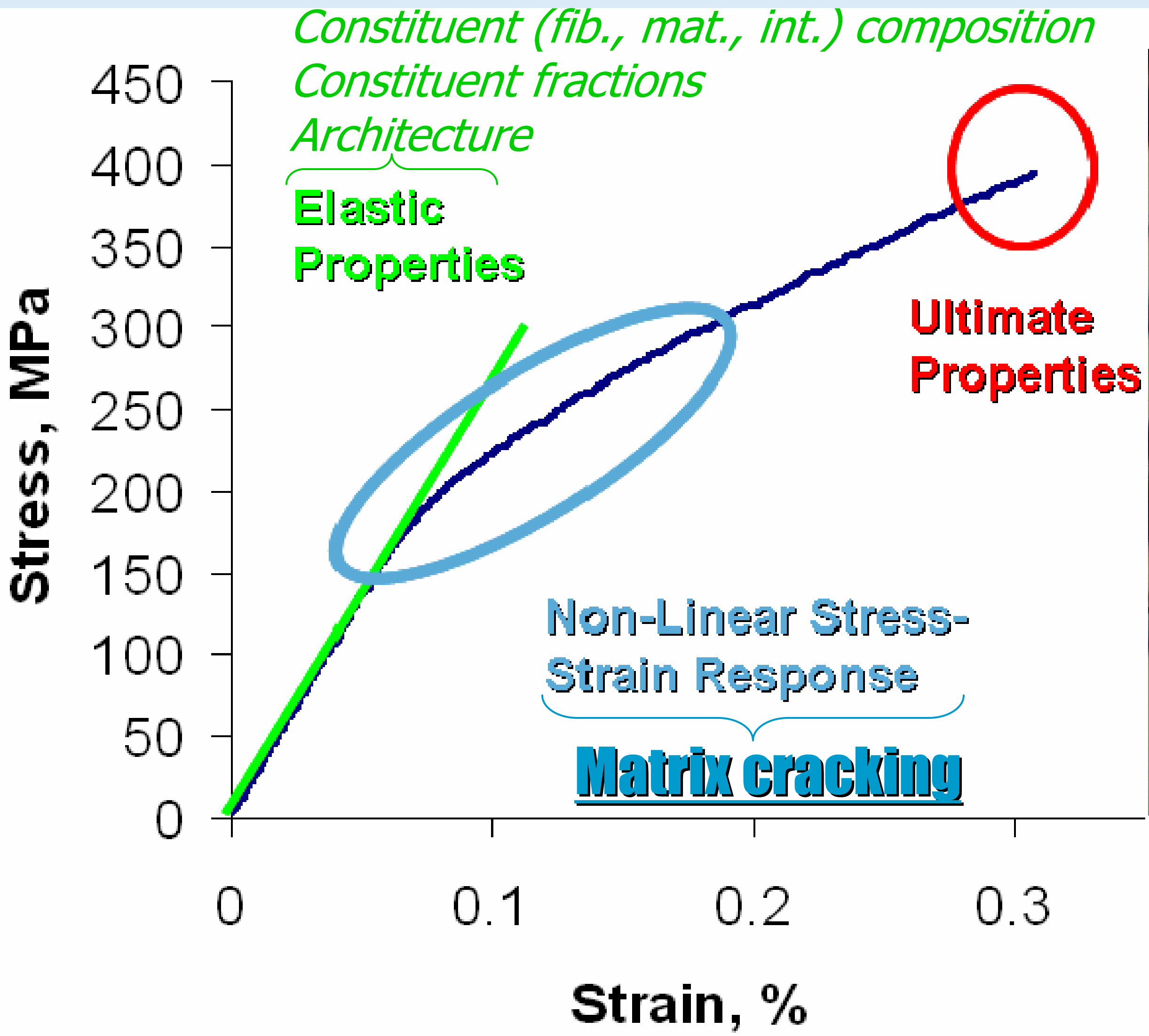


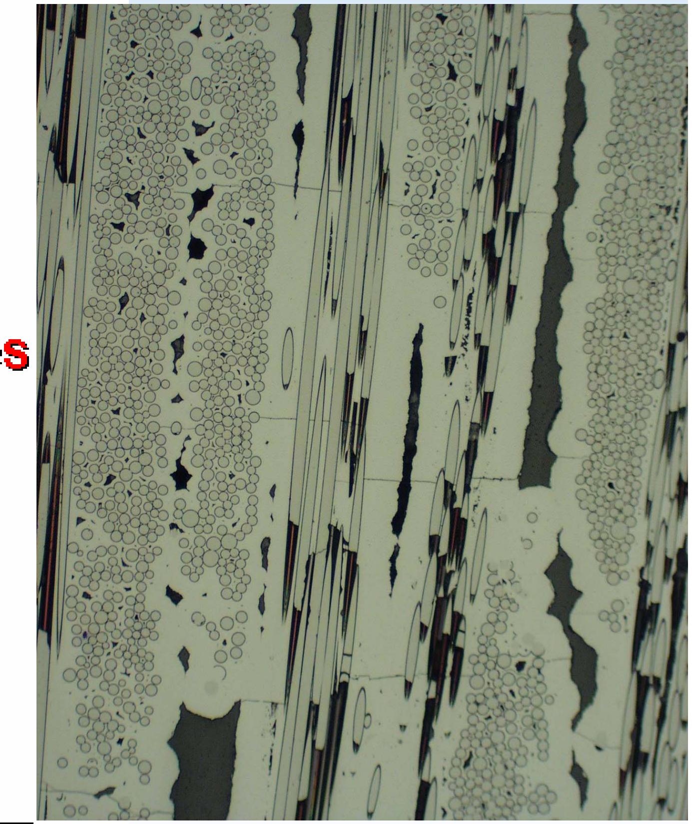
Inlet Turbine Vane



Thin-cooled structure

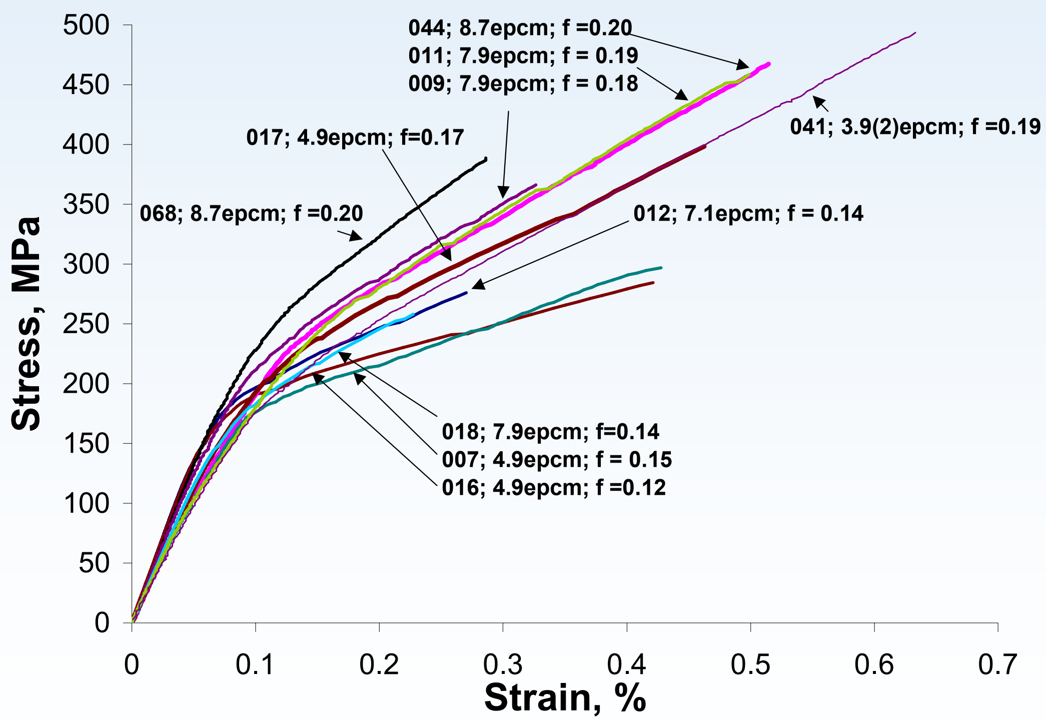
Objective: Model σ/ε Behavior of CMC's





However, composites will vary throughout a component…

- Constituent contents
- Number of plies
- Local architectures
- Thickness
- Processing uniformity
- Curvature



For example, Sylramic fiber-reinforced melt-infiltrated composites (2D 5 harness satin) that vary in:

-Number of plies by factor of 2
-Thickness by factor of 2
-Tow ends per cm in weave
-Matrix content
-Fiber content
-Size of tow
-Debonding interface

Typical approaches to modeling mechanical properties involve making many panels of the "same thing" in order to get statistical variations.

There is a greater need to model composite behavior as a function of constituent and architecture variation for design of components and predicting use-life.

Outline

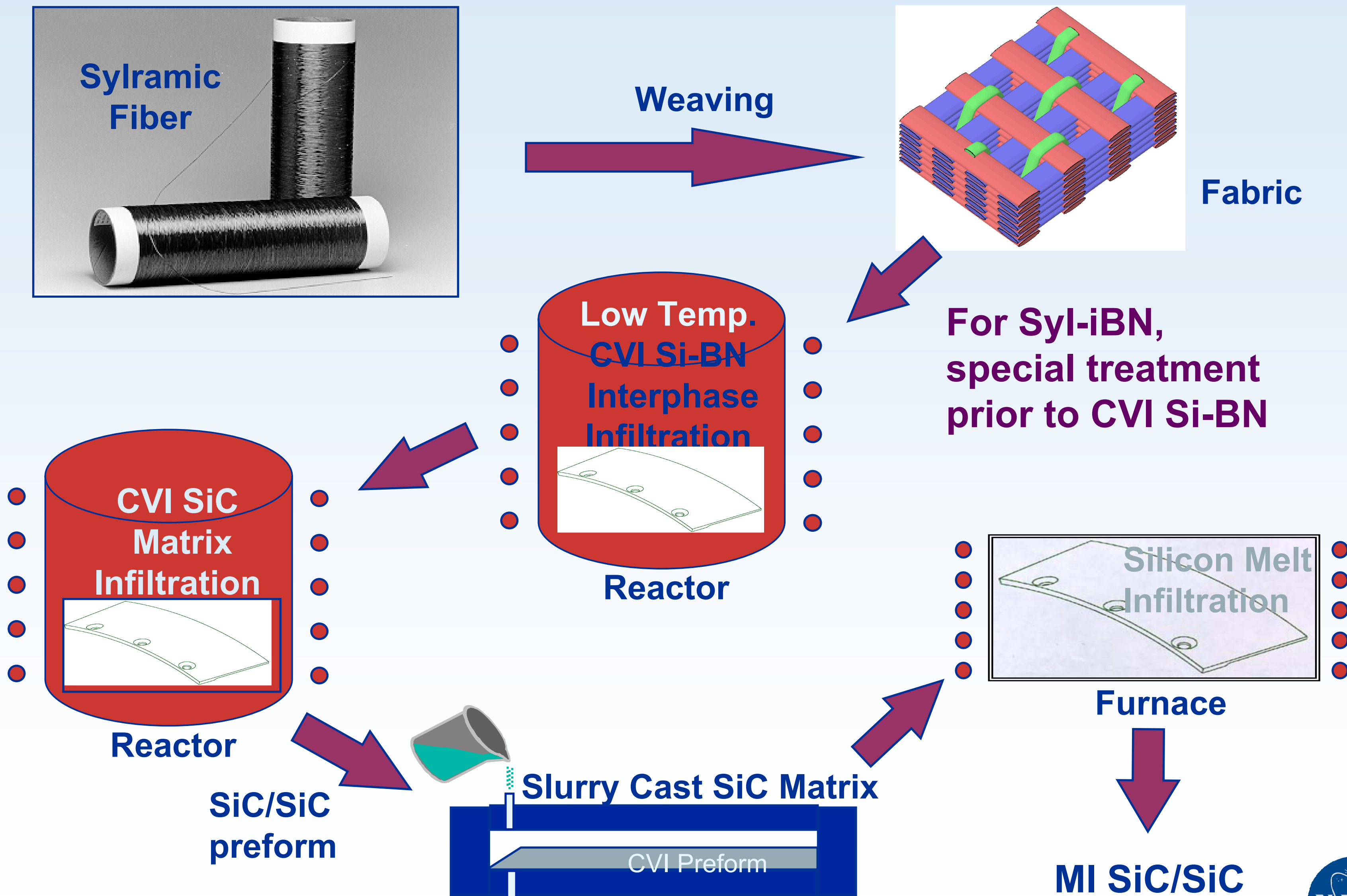
Composite processing

Use of Modal Acoustic Emission

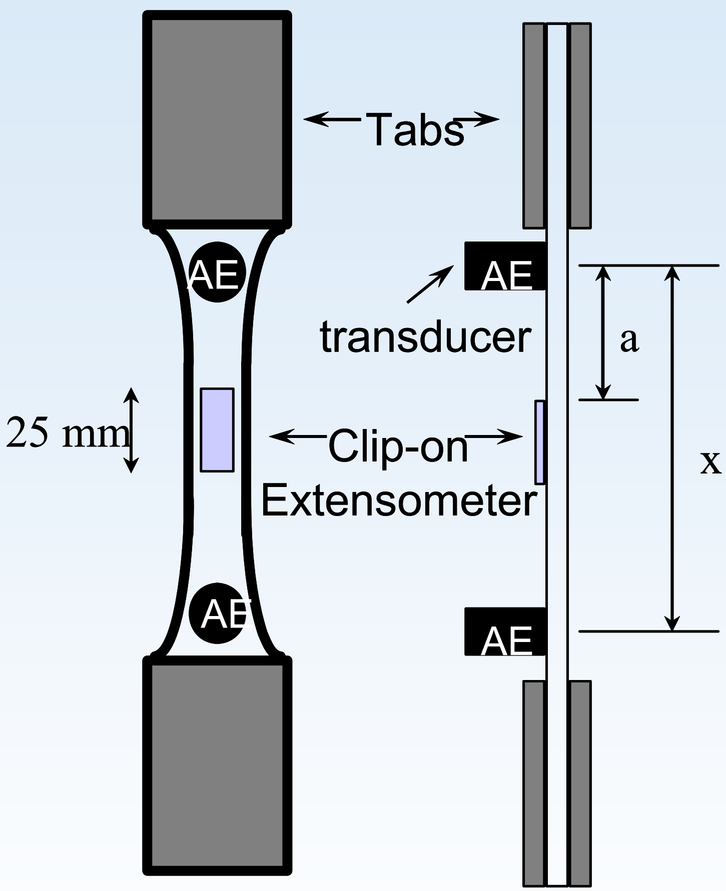
3 Examples of Non-linear σ/ε Behavior
(orthogonal direction)

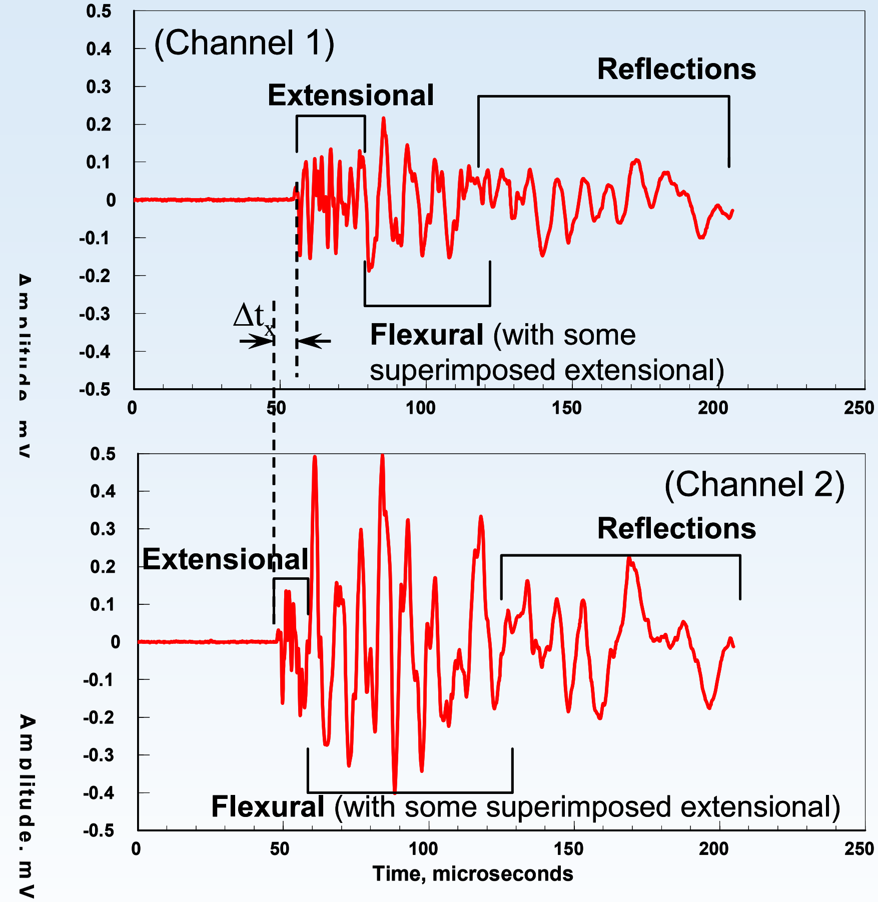
- 2D Melt-infiltrated system
- 3D Melt-infiltrated system
- 2D CVI SiC System

Standard Slurry Cast Melt-Infiltrated (MI) 2D & 3D Woven Composites



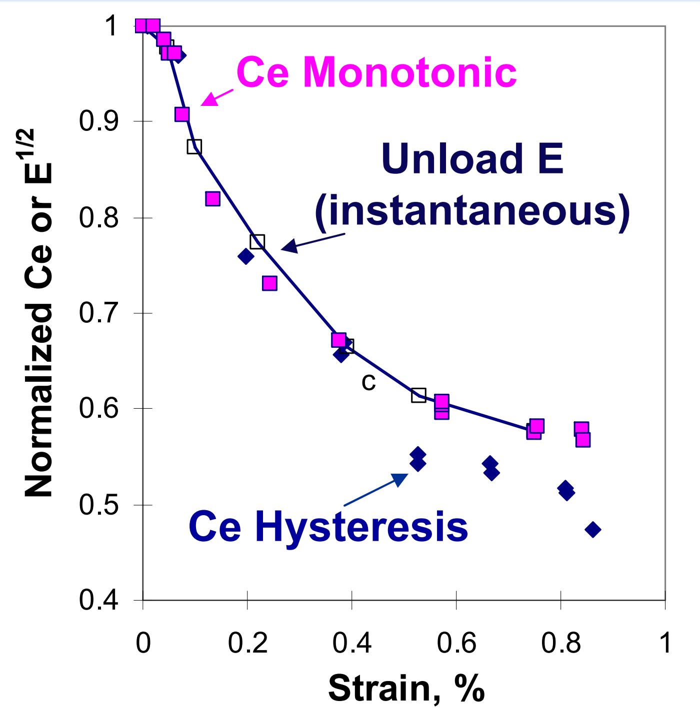
Modal Acoustic Emission of CMCs

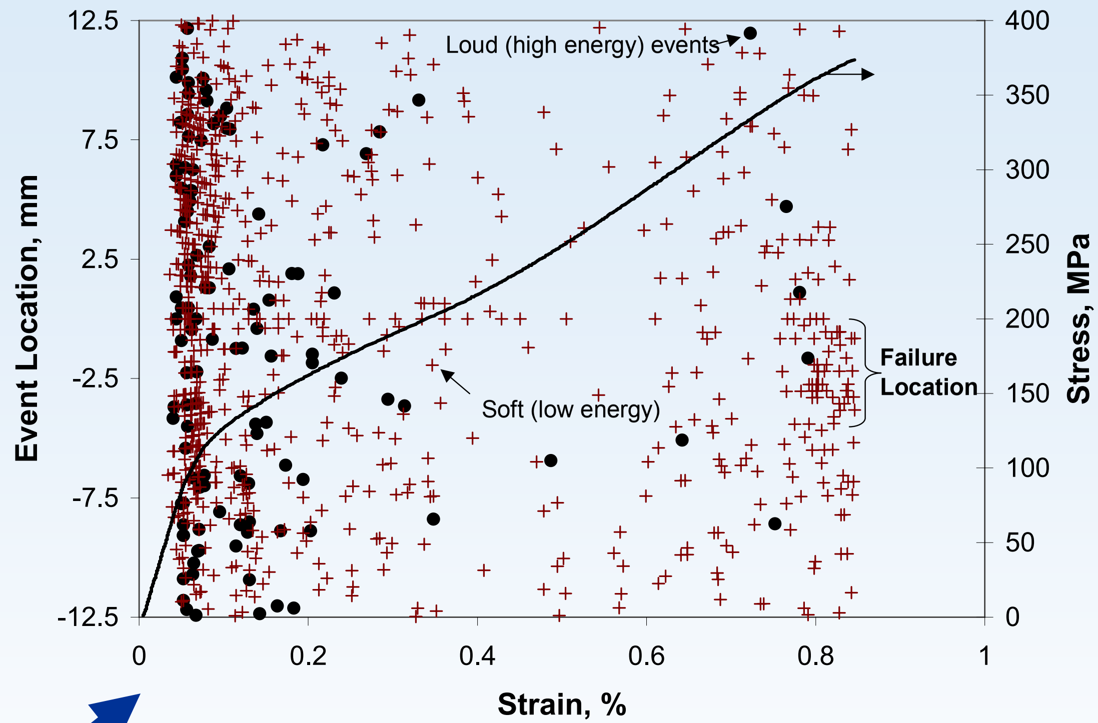




- •Locate damage events and failure events → Δt
- •Monitor stress(or time)-dependent matrix cracking → Cumulative AE Energy
- •Identify damage sources, e.g. matrix cracks, fiber breaks → Frequency
- •Measure stress(or time) dependent Elastic Modulus → Speed of sound

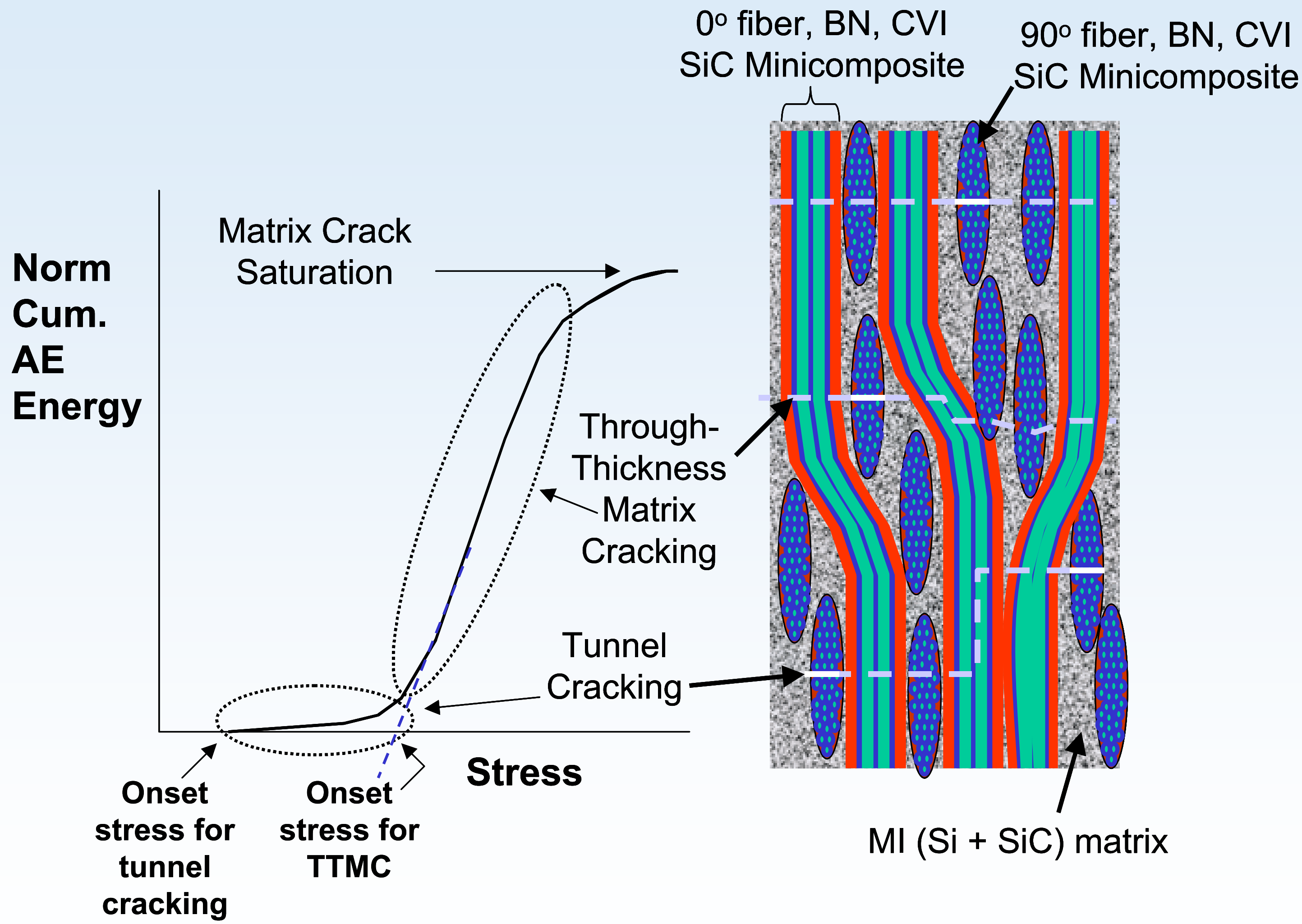
An Example: Hi-Nicalon/CVI SiC





Normally, using a threshold voltage technique for location gives ~ ± 2mm accuracy. For 3D composites, _each event was examined "by hand"_ to determine 1st peak (± 0.25 mm)!

Relationship Between AE and Matrix Cracking



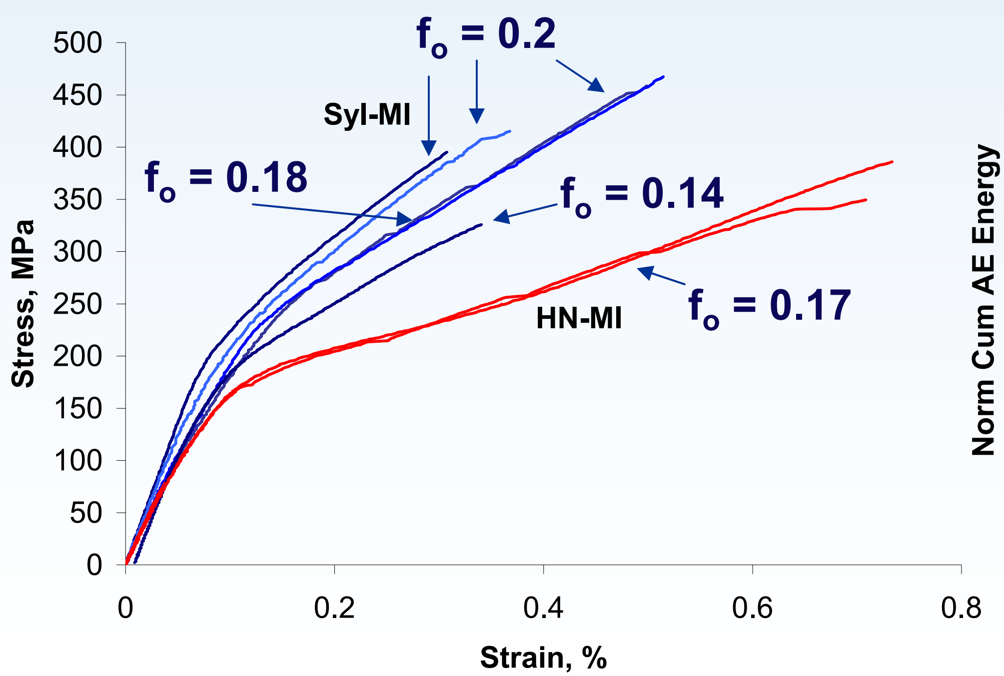
See Evans et al., Cox and Marshall, Chou et al, Lamon et al., etc…

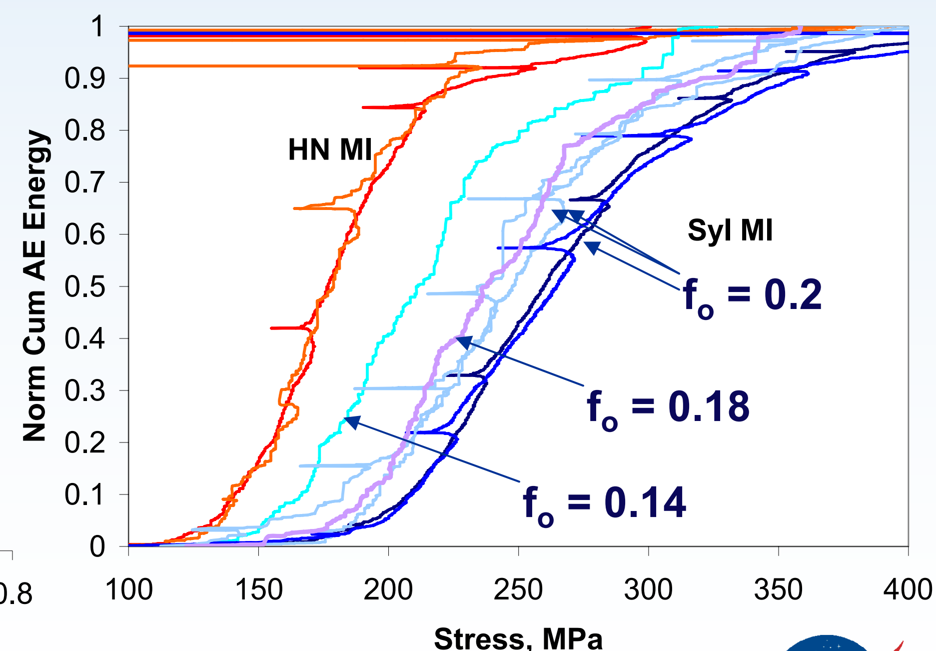
Example #1: 2D Woven Melt-Infiltrated Systems When Stressed in Orthogonal Direction

HN and Sylramic (iBN) Fiber-types

Stress-Strain and AE for Different Composite Panels

- Acoustic Emission used to monitor matrix crack density and derive a matrix crack distribution
- Applied to Sylramic-based and Hi-Nicalon-based composite systems *<u>that vary by a factor of two</u>* in number of plies, thickness, tow ends per cm, and number of fibers per woven tow





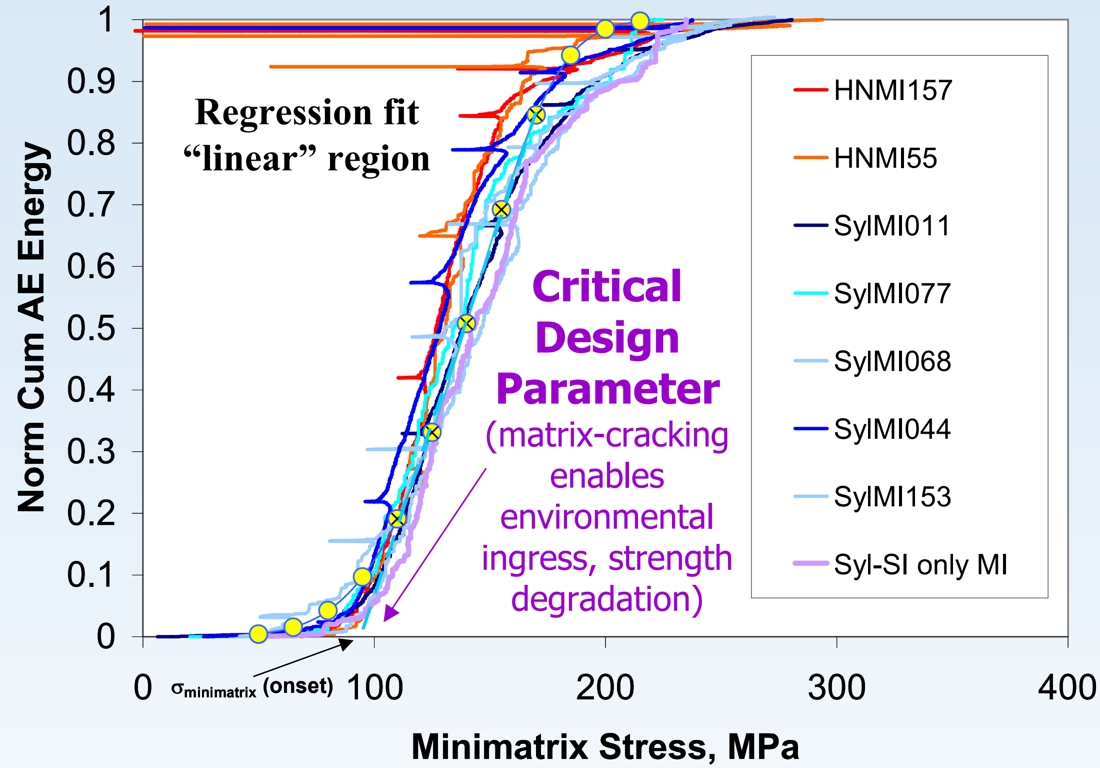
For Orthogonal Composites, the 90° Fiber-Tows are the Source for Matrix Crack Formation

- The stress that acts on the 90° fiber-tows is the stress in the composite "outside" of the load-bearing fiber, BN, CVI SiC minicomposite, i.e., the ***"mini-matrix" stress:***

$$\sigma_{\min i\,matrix} = \frac{(\underbrace{\sigma_c}_{\text{Applied composite stress}} + \underbrace{\sigma_{th}}_{\text{Net residual stress}})}{\underbrace{E_c}_{\text{Composite modulus}}}\left(\frac{E_c - f_{\min i}\underbrace{E_{\min i}}_{\text{0° minicomposite modulus (rule of mixtures)}}}{1 - \underbrace{f_{\min i}}_{\text{Fraction of minicomposite in 0° direction}}}\right)$$

All the information required is obtained from RT stress-strain test (or sound techniques) and processing data sheet.

A very simple relationship for matrix cracking in 2D MI SiC/SiC Composites



Norm Cum AE Energy

$$\rho_c(\sigma_{\min imatrix}) = \rho_c \underbrace{\left[1 - \exp\left(-\left(\frac{\sigma_{\min imatrix}}{\sigma_o}\right)^m\right)\right]}_{\text{Norm Cum AE Energy}}$$

ρ_c = final crack density
~ 2.5/mm for Hi-Nicalon
~ 10/mm for Sylramic

σ_o = 150 MPa; m = 5

Can Then Use to Model σ/ε

Determine $\rho_c(\sigma_c)$ from $\rho_c(\sigma_{minimatrix})$ relationship:

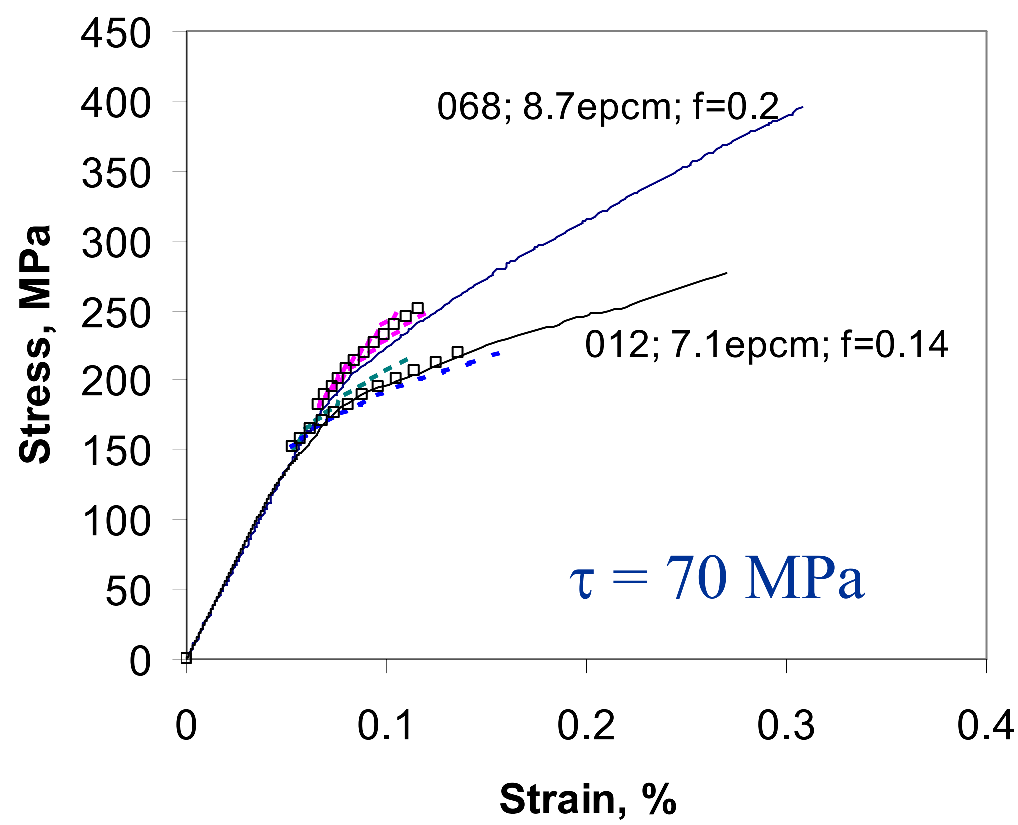
$$\varepsilon = \sigma/E_c + \alpha\delta(\sigma)\rho_c/E_f\ (\sigma + \sigma_{th})$$

Where $\delta = \alpha\, r\, (\sigma + \sigma_{th}) / 2\tau$

$\alpha = (1-f)\, E_m / f\, E_c$

* After Curtin and Pryce and Smith

Sylramic; BN; MI SiC



Starting point for life-degradation models

Example #2: 3D-Orthogonal Composites With Different Z-Fiber Types

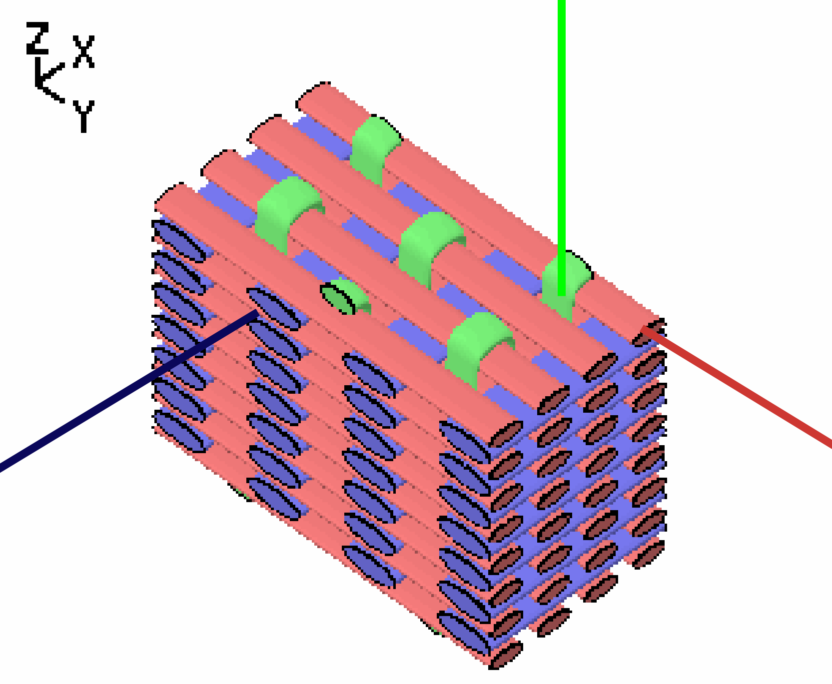
X- and Y-direction Fibers = Sylramic or Syl-iBN

MI Composites

Woven 3D-Orthogonal Composites with ***Different*** Z-Fiber Types

<u>Z-Direction:</u>

ZMI (800 fiber/tow)
T300 (1000 fiber/tow)
Rayon (400 fiber/tow)



<u>X-Direction:</u>

Two Sylramic Tows (1600 fibers)

10 epi

7 plies

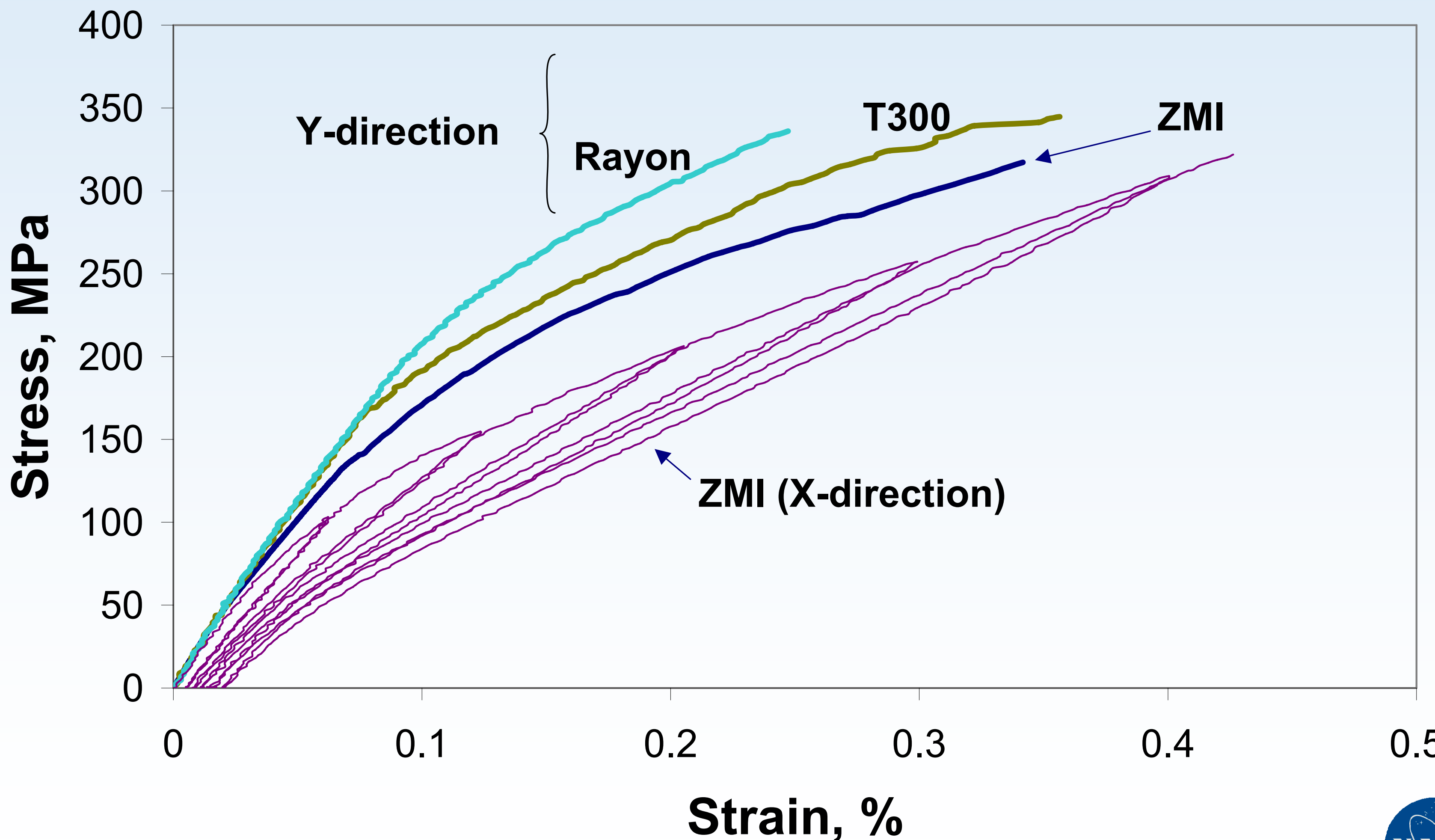
<u>Y-Direction:</u>

One Sylramic Tow (800 fibers)

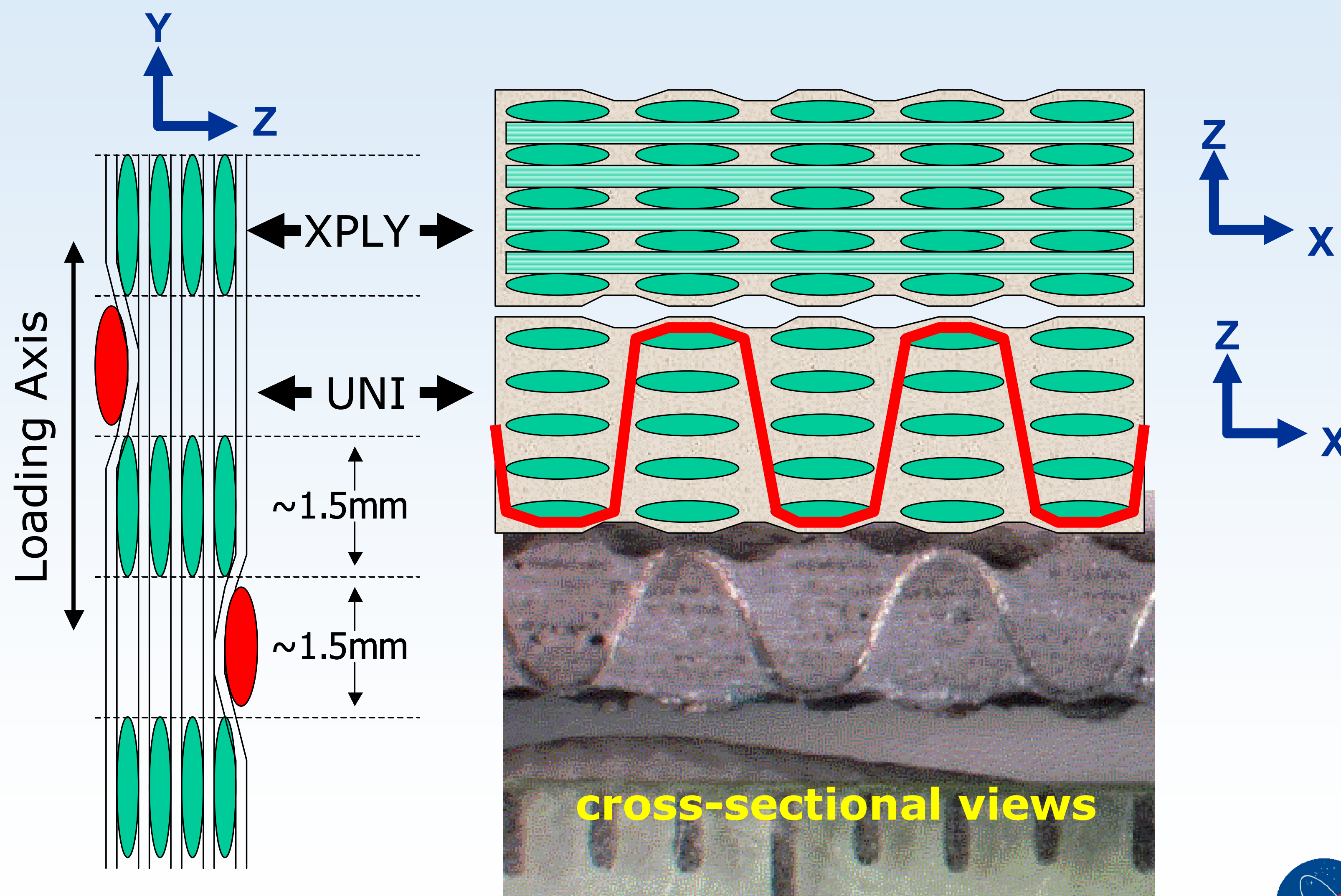
18 or 20 epi

8 plies

3D Orthogonal σ/ε Behavior



Loading in the Y-Direction

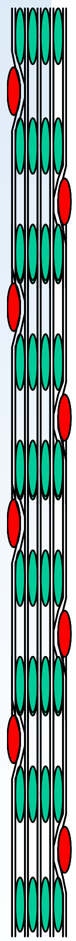


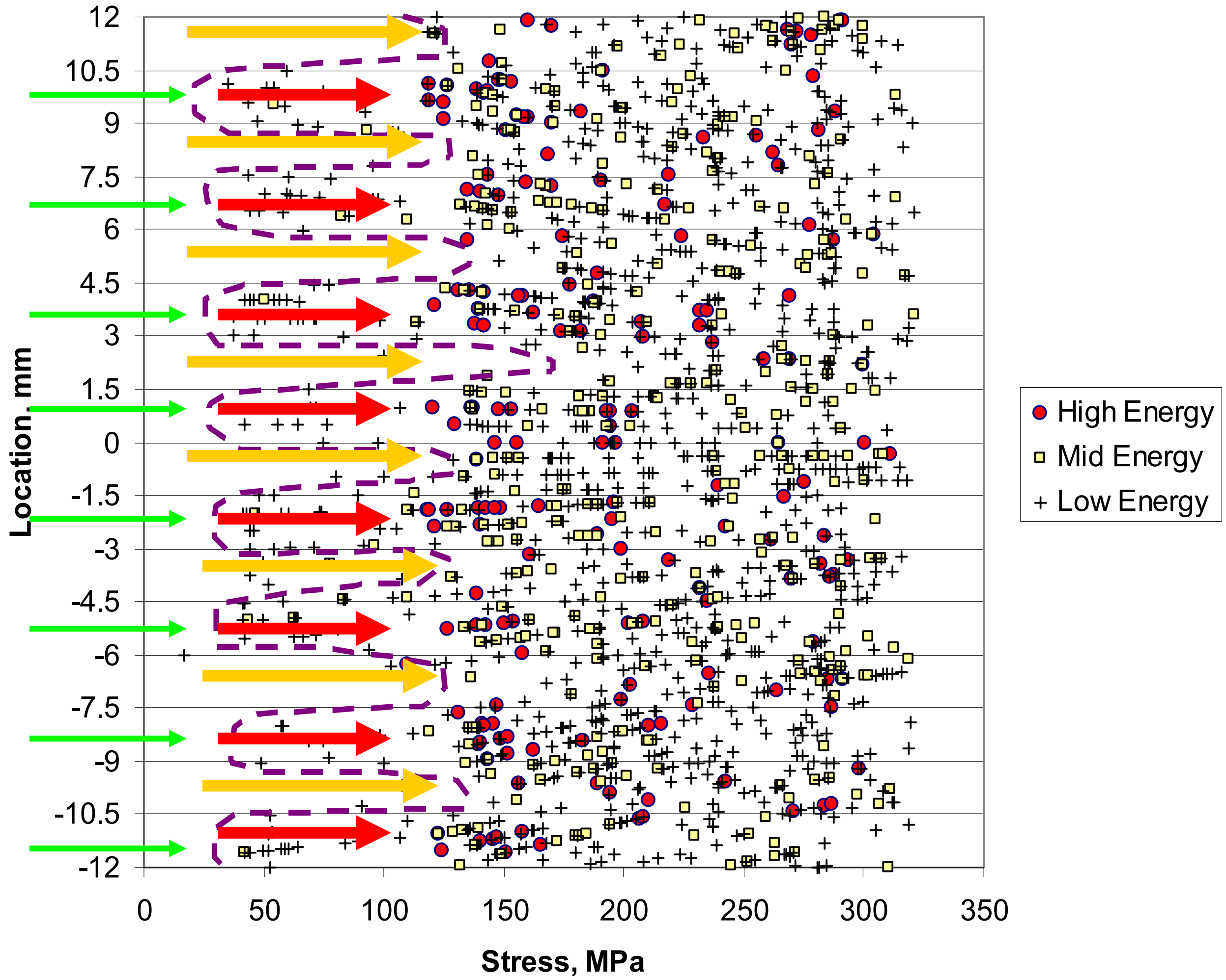
ZMI Composite

(1) Matrix micro-cracks originate in the UNI sections (low energy AE)

(2) Large matrix cracks form in the UNI sections (High energy AE)

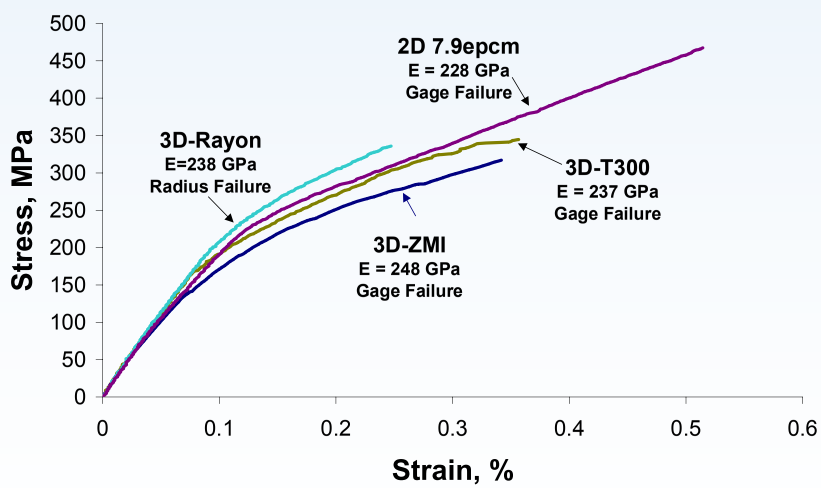
(3) Matrix cracks form in XPLY regions

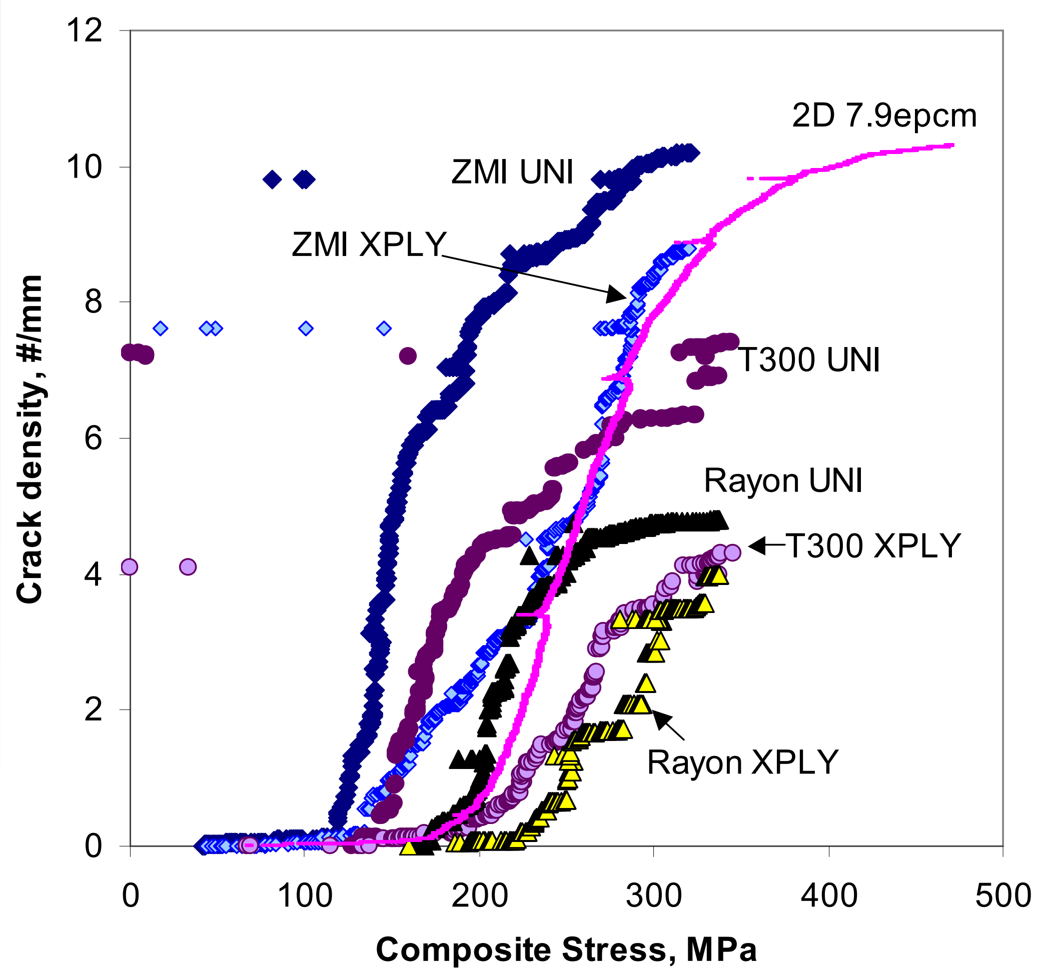




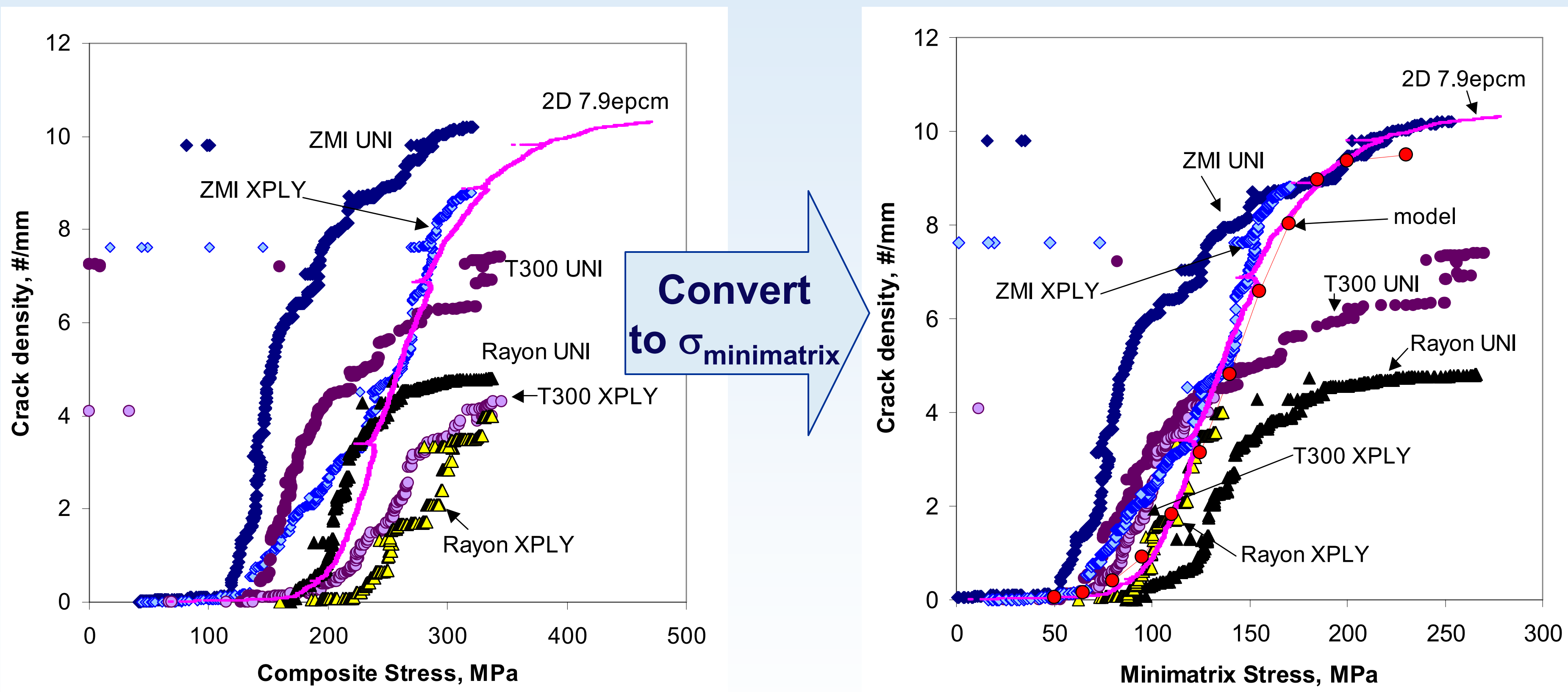
Stress Distributions For Three Y-Direction Oriented 3D Composites and Standard 2D Composite

- Wide range of matrix cracking stress-distributions
- XPLY cracking stresses always higher than UNI cracking stresses
- Rayon > T300 > ZMI



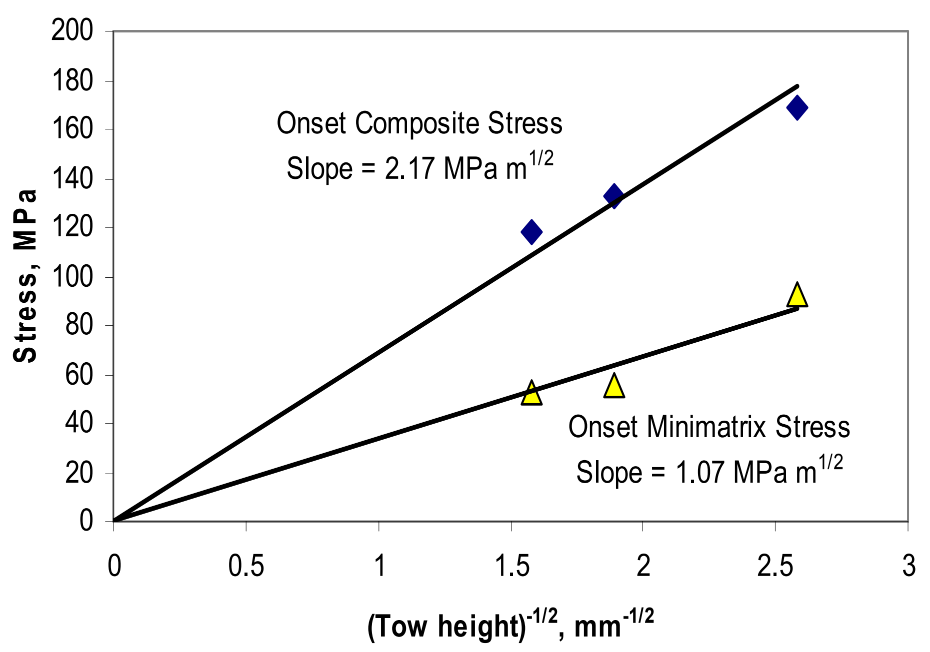


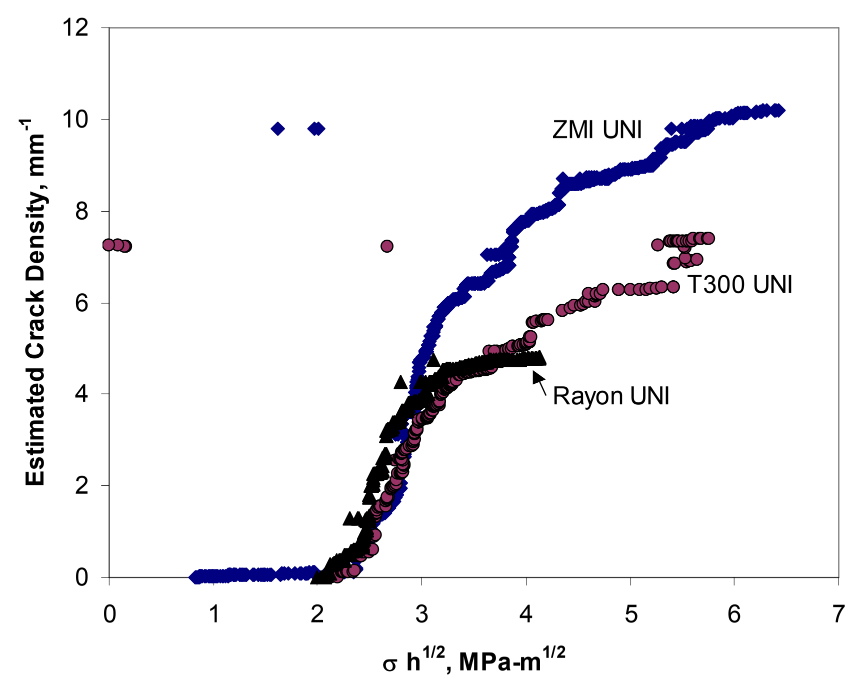
Minimatrix Stress Dependence for Matrix Cracking in 3D Composites



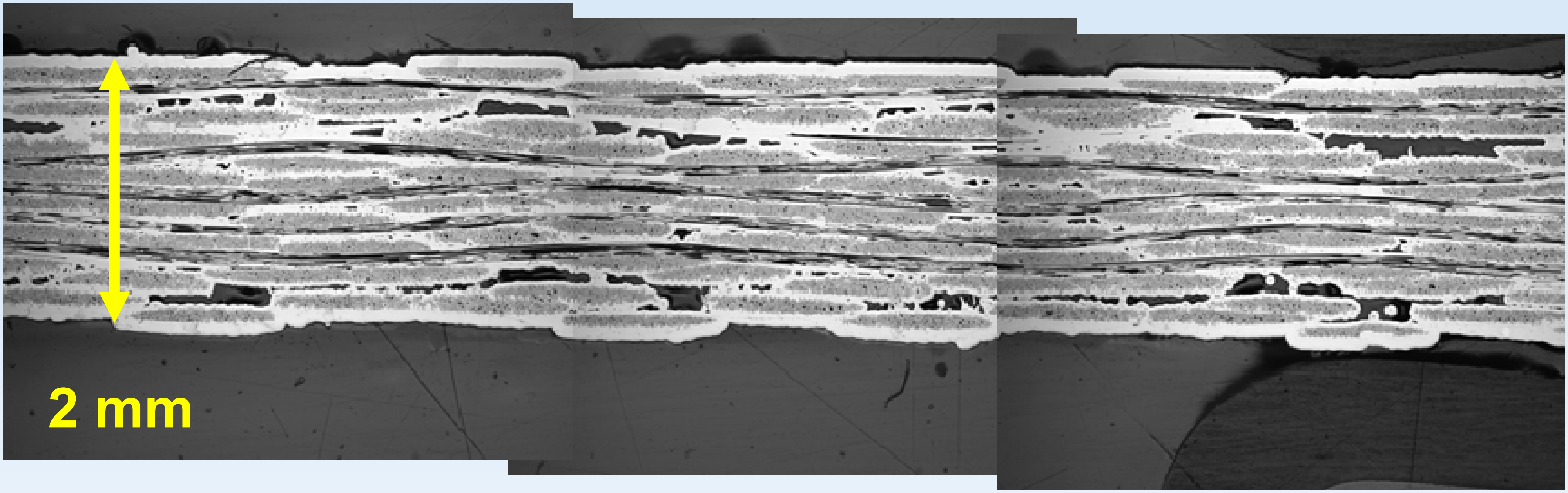
- **Good correlation for XPLY regions**
  - **UNI regions unaffected**

UNI Regions Dependent on Height of Z-Tow: Griffith-type Relationship





* Tow height measured 0.5 mm from surface

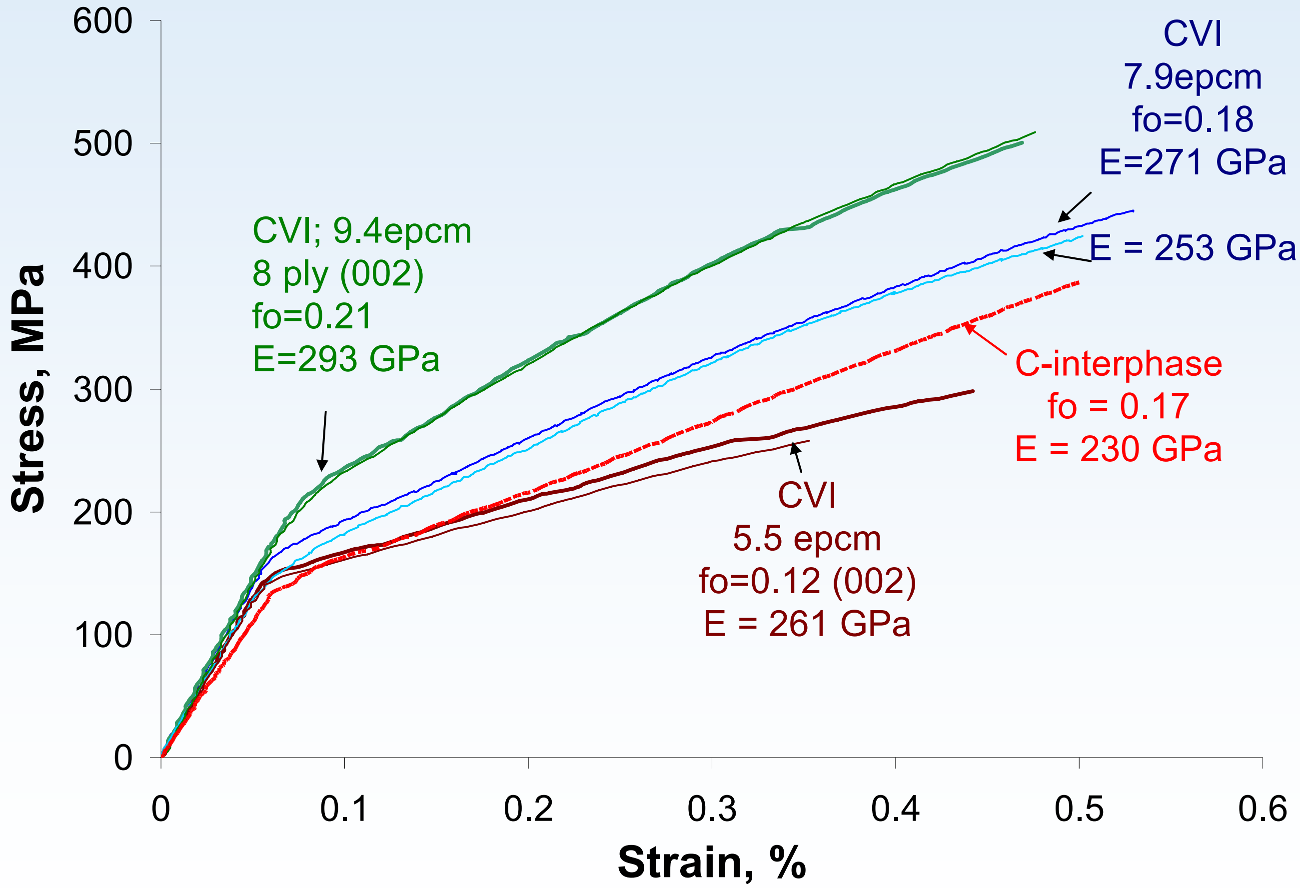


Example #3: 2D CVI SiC Composites

Variation in orthogonal fiber-loading in order to raise matrix cracking stresses.

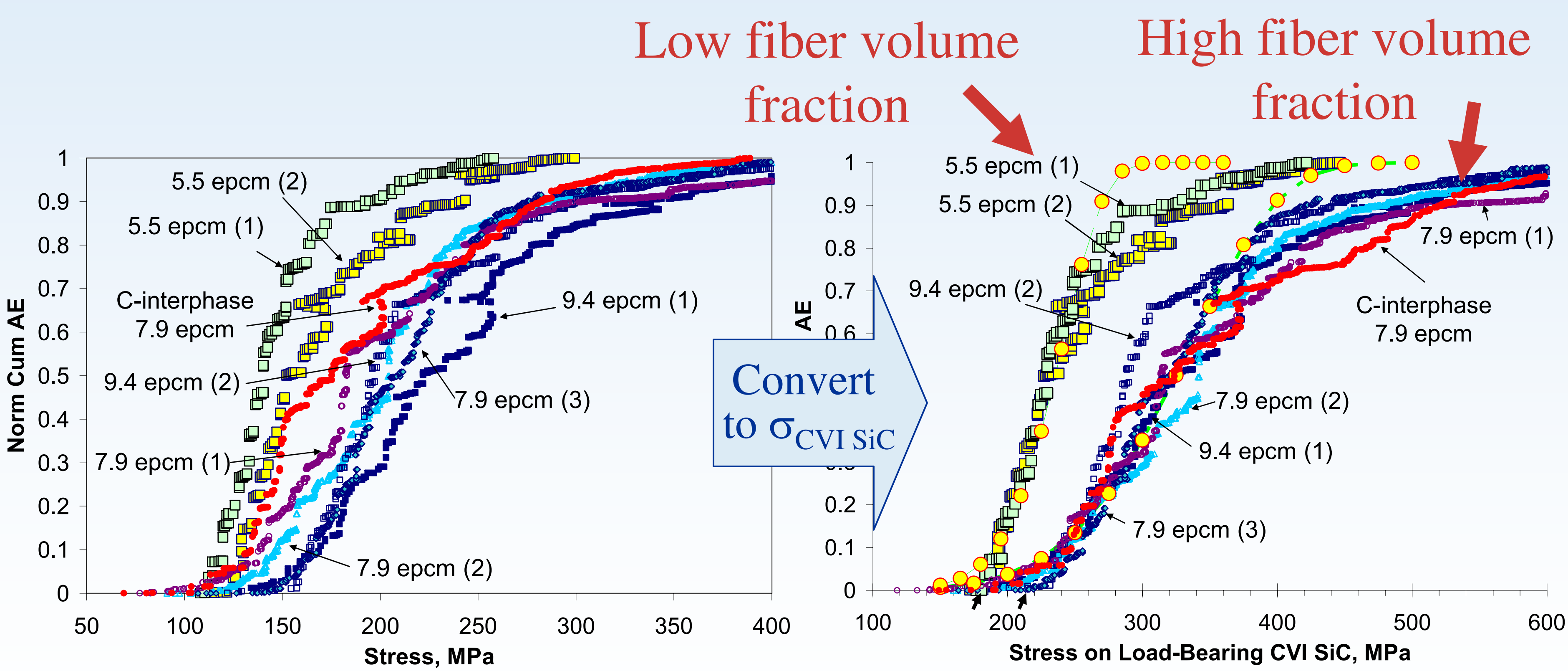
Syl-iBN, BN interphase, CVI SiC Matrix Composites

- Balanced weave = 7.9 tow ends per cm
- Unbalanced weave = 9.4 x 5.5 tow ends per cm

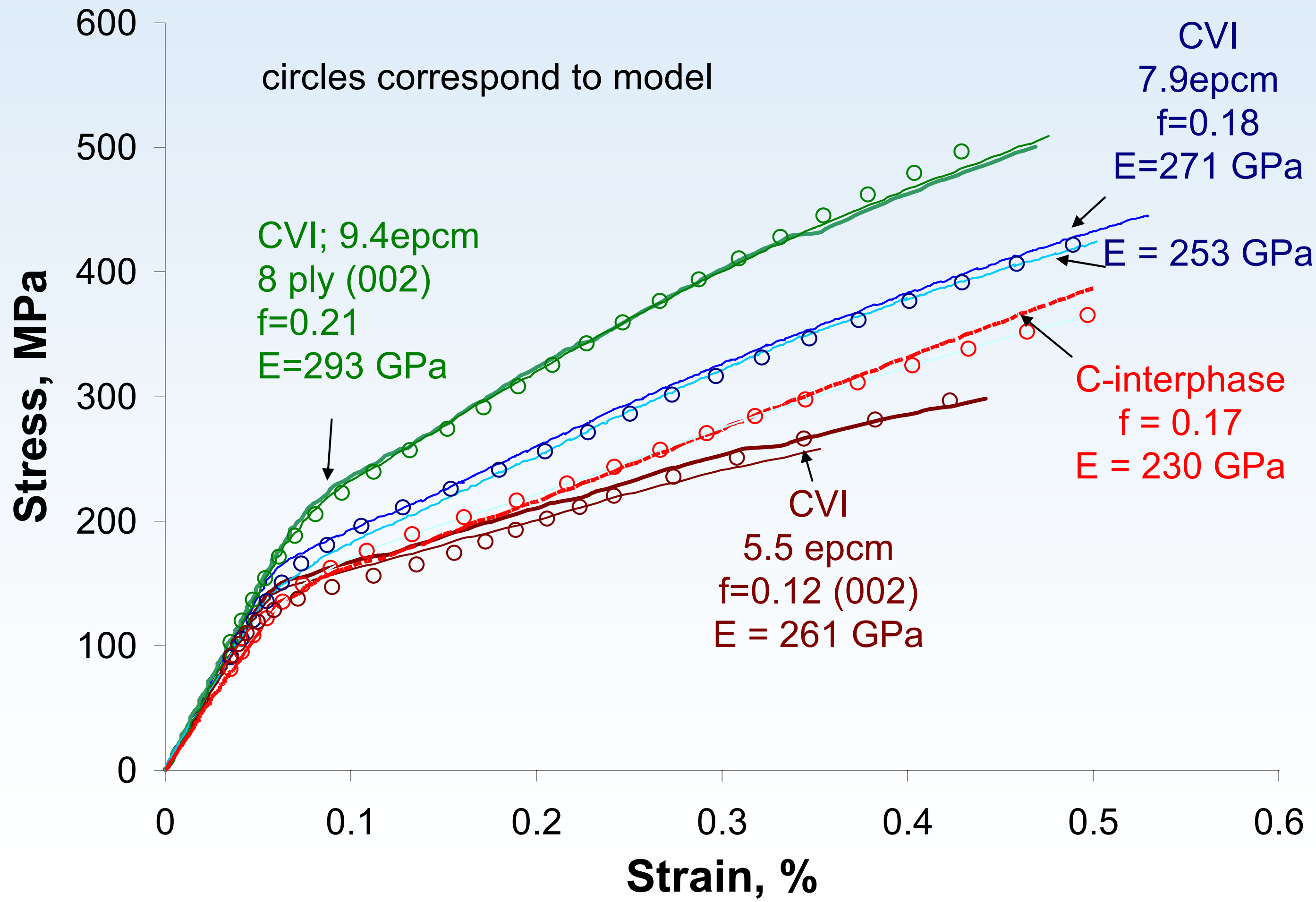


Matrix Cracking Dependent on Stress in CVI SiC and "Bridging Condition"

Stress in load-bearing CVI SiC: $\sigma_{SiC} = (\sigma/E_c)E_{SiC}$



Good Prediction of σ/ε Behavior



Conclusions

- Robust relationships have been determined to describe matrix cracking in a wide range of "dense-matrix" SiC/SiC composites when stressed in orthogonal directions
- These can be implemented in design of components with variation in constituent content, architecture, and shape (for orthogonal directions)
- The matrix cracking behavior serves as the "starting point" for life-modeling at stresses above matrix cracking limits

Acknowledgments

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Effect of Tow Size and Shape:

Single-Tow vs. Double-Tow Woven Composites

- **Identical fiber volume fraction; Both five-harness satin**